

Five nights of intensive R - and V -band photometry of QSO 0957+561A,B

J. E. Ovaldsen,^{1*} J. Teuber,² R. Stabell¹ and A. K. D. Evans¹

¹*Institute of Theoretical Astrophysics, University of Oslo, P. O. Box 1029, Blindern, N-0315 Oslo, Norway*

²*Centre for Advanced Signal Processing, Copenhagen, Denmark*

Accepted 2003 July 8. Received 2003 May 13

ABSTRACT

We present R - and V -band photometry of the gravitational lens system QSO 0957+561 from five nights (one in 2000 January and four in 2001 March, corresponding to the approximate time-delay for the system) of uninterrupted monitoring at the Nordic Optical Telescope. In the photometry scheme we have stressed careful magnitude calibration as well as corrections for the lens galaxy contamination and the crosstalk between the twin (A and B) quasar images. The resulting, very densely sampled light curves are quite stable, in conflict with earlier claims derived from the same data material. We estimate high-precision timelag-corrected B/A flux ratios in both colour bands, as well as $V - R$ colour indices for A and B, and discuss the short time-scale variability of the system.

Key words: Cosmology: gravitational lensing – Quasars: individual: QSO 0957+561 – Techniques: photometric – Methods: data analysis

1 INTRODUCTION

More than 20 years of monitoring of the ‘classical’ double quasar QSO 0957+561A,B (Walsh et al. 1979) has shown that this interesting object exhibits variability at several levels and time-scales. This variability has been extremely useful for such diverse applications as, e.g., estimating the Hubble constant via the ‘Refsdal time delay method’, constraining the continuum-emitting region of the quasar, and probing the mass distribution in the lens galaxy and its surrounding cluster. Despite its relative photometric simplicity, QSO 0957+561 ($z_{\text{QSO}} = 1.41$, $z_{\text{lens}} = 0.36$, $\theta_{\text{AB}} \approx 6.2$ arcsec) has nevertheless proved more unwieldy than initially hoped. In this context we note that even the best sampled light curves may exhibit artificial fluctuations or seeming correlations, and the task of distinguishing between physical events (whether intrinsic or microlensing-induced) and spurious ones is not necessarily straightforward.

In this paper we employ our newly developed photometry scheme (Ovaldsen et al. 2003) and present two-colour photometry for QSO 0957+561A,B based upon about 1200 CCD images from five observing nights, four of which are consecutive. This densely sampled, high-quality data set allows us to, e.g., constrain the short time-scale variability and the noise level to be expected in past and future investigations on the same theme. Part of this study constitutes a re-reduction of existing data, and our results are at

variance with previously published work (Colley et al. 2002, 2003, hereafter C02 and C03); for instance, we find no support for the hourly variability invoked by the above authors to facilitate a time delay determination with accuracy of a fraction of a day (417.09 ± 0.07 d).

The data material is described in Sect. 2, while a short outline of the photometric procedure is given in Sect. 3. Photometry for comparison stars as well as for the A and B quasar components is presented and commented in Sect. 4. Sect. 5 concludes with a discussion and a summary.

2 DATA SET

Our original data set consists of 976 R -band and 229 V -band CCD frames obtained with the 2.56-m Nordic Optical Telescope (NOT) on La Palma, Canary Islands, Spain, using the ALFOSC instrument.¹ The observations were made on 2000 January 25–26 and during the four nights 2001 March 14–18, and were part of the ‘QuOC Around the Clock’ 2000/2001 campaigns, designed to compare observing runs separated by the assumed time delay for QSO 0957+561 of ~ 416 days; see C02 and C03, where a reduction of the R -band data from the same set is discussed. (Note that investigations

¹ ALFOSC is owned by the Instituto de Astrofísica de Andalucía (IAA) and operated at the NOT under agreement between IAA and the NBIfAFG of the Astronomical Observatory of Copenhagen.

* E-mail: j.e.ovaldsen@astro.uio.no

in recent years seem to favour a lag around 425 days, see Ovaldsen et al. 2003 and references therein.) The detector is a $2k \times 2k$ CCD with a gain of $1 \text{ e}^-/\text{ADU}$ and readout noise of approx. $6 \text{ e}^-/\text{pixel}$. The nominal pixel size is 0.188 arcsec .

All images were pre-processed with bias subtraction and flat-fielding, exclusively by means of sky flats. The averaged flats typically represented a photon number 100–500 times the background level (which was between 100 and 600 photons) in the science frames. According to the online specification of the CCD chip, it contains 8 bad columns, 10 traps, and many dark ‘speckles’. Deplorably, we had to discard 107 frames ($97 R + 10 V$) because one or both of the quasar components fell too close to a defective column.

The seeing varied from 0.6 to 2 arcsec (median value ≈ 0.9). The point sources on the frames were usually slightly elliptical, with a median axis ratio of 1.1. However, some PSFs were highly elliptical, especially when the object was near the horizon.

3 PHOTOMETRY SCHEME

The photometry package used to reduce the CCD images was developed by us (JT and JEO). The method is described in Ovaldsen et al. (2003), where it was applied to a five-year archival data set of QSO 0957+561; a full treatment is given in Ovaldsen (2002). Features include automatic source detection and localisation, field star aperture and PSF photometry, magnitude calibration, and aperture and PSF photometry of the twin quasar images (after lens galaxy subtraction and crosstalk correction).

3.1 Field star photometry and calibration

To obtain a reliable magnitude calibration, we believe it is imperative to include as many comparison stars as possible *and* to check their internal brightness consistency. We apply aperture photometry, using a 3 arcsec radius, to 7 comparison stars in the field (F, G, H, E, D, X, and R, see fig. 1 in Ovaldsen et al. 2003). The measured total intensities of the field stars are compared to the reference values (see below) to estimate the frame conversion factor. If more than one outlier is present, or if the conversion factor is statistically ambiguous, the frame is discarded. The obvious rationale for this policy is that if consistent photometry for the reference stars is impossible, it will be even more so for the quasar components.

Reference R -magnitudes for the comparison stars were kindly supplied by R. Schild (private communication). Lacking a proper set of reference V -magnitudes, we used the $V - R$ colour terms of Serra-Ricart et al. (1999) for the stars H and D to convert our R -magnitudes for these two stars into V . Finally, the overall R - and V -magnitude scales were adjusted to a best fit with the reference values.

It should be noted that the above procedure implies a large difference between our reference R -magnitudes and those of Serra-Ricart et al. We would like to stress, however, that this is not unusual. The reference magnitudes encountered in the literature (e.g. Keel 1982, Vanderriest et al. 1989, and Serra-Ricart et al.), may differ by as much as 0.4 mag for a single star!

3.2 Photometry of the quasar images

The distinctive feature of QSO 0957+561 is the seeing-dependent contamination by the lensing galaxy, denoted G1, particularly of the closely juxtaposed B image. To correct for this influence, we construct and subtract from each frame a galaxy model. Using a composite R -band brightness profile derived by Bernstein et al. (1997) and the appropriate ellipse parameters, a seeing-free G1 model is synthesised and convolved with the PSF of the actual frame (see Ovaldsen 2002 for details, especially as regards the magnitude calibration). The position and orientation is determined using the astrometry of Bernstein et al. and the calculated centroids of the quasar images. Note that the brightness level is adjusted by an amount estimated by a three-component (A, B, G1) simultaneous fitting in the entire data set. Without better options (see, however, Teuber et al. 2003), we use the same galaxy profile in the V -band, decreasing the brightness level accordingly.

After the galaxy subtraction, the PSF is used to correct for cross-contamination between the quasar components. Refraining from performing a PSF flux estimation as such, we have chosen the hybrid method consisting of a ‘PSF cleaning’ of one of the two quasar images followed by an aperture flux measurement of the other, and vice versa. If necessary, the procedure may be performed iteratively.

Separate corrections for galaxy contamination and aperture crosstalk are vital for achieving high-precision photometry, especially when there are large variations not only in seeing but also PSF ellipticity.

4 PHOTOMETRIC RESULTS

4.1 Field stars

Our calibration procedure accepted 817 (out of 879) R -band frames and 206 (out of 219) V -band frames. Photometry results for the comparison stars are summarised in Tables 1 and 2 for the R - and V -band, respectively.

When presenting the quasar light curves (Sect. 4.3), we include the results for the fainter star, R, the brightness of which is comparable to that of the quasar components.

4.2 Galaxy contribution and aperture crosstalk

From the subtraction procedure described above, we found that, depending on seeing, the galaxy light in the R -band amounted to 18.24–18.26 and 20.45–20.25 mag in the B and A apertures, respectively. In the V -band, the corresponding values were 19.34–19.38 mag (B) and 21.50–21.30 mag (A). So, as seeing deteriorates, galaxy light spills out of the B aperture and into the A aperture. Crosstalk between the twin quasar images was less than 1 per cent for seeing values below 2 arcsec. Note that both corrections are functions also of PSF ellipticity, that is, axis ratio and position angle.

4.3 The A and B quasar light curves

Figs. 1 (2000 January), 2 and 3 (2001 March) display light curves of the A and B quasar images and the R star in the R - and V -bands. No outliers have been removed. The

Table 1. Aperture photometry of the comparison stars in the *R*-band. For each star the mean magnitude and standard deviation are tabulated, along with the mean of the individual formal errors, and reference magnitude. See text for explanation of the calibration.

| Star | Mean <i>R</i> -mag | σ_{mag} | Mean formal error | Ref. mag |
|------|--------------------|-----------------------|-------------------|----------|
| F | 13.759 | 0.0016 | 0.0013 | 13.758 |
| G | 13.731 | 0.0013 | 0.0013 | 13.731 |
| H | 13.973 | 0.0016 | 0.0015 | 13.972 |
| E | 14.778 | 0.0020 | 0.0020 | 14.778 |
| D | 14.513 | 0.0023 | 0.0018 | 14.513 |
| X | 13.425 | 0.0014 | 0.0011 | 13.425 |
| R | 16.328 | 0.0046 | 0.0045 | 16.329 |

Table 2. Same as Table 1, but in the *V*-band.

| Star | Mean <i>V</i> -mag | σ_{mag} | Mean formal error | Ref. mag |
|------|--------------------|-----------------------|-------------------|----------|
| F | 14.093 | 0.0015 | 0.0014 | 14.093 |
| G | 14.054 | 0.0013 | 0.0013 | 14.054 |
| H | 14.497 | 0.0016 | 0.0016 | 14.497 |
| E | 15.247 | 0.0021 | 0.0021 | 15.247 |
| D | 14.948 | 0.0021 | 0.0019 | 14.948 |
| X | 13.770 | 0.0014 | 0.0011 | 13.770 |
| R | 17.088 | 0.0061 | 0.0060 | 17.086 |

nightly mean brightnesses of the same objects, along with the corresponding standard deviations, are given in Table 3.

Despite considerable hourly variations of such decisive observational parameters as airmass, seeing, PSF ellipticity, sky level, and S/N-ratio, the light curves exhibit no dramatic features and appear quite constant during each night. The nightly standard deviations for the quasar components range from 3.9 to 6.4 mmag, to be compared with the mean

of the individual formal errors for each night of 4.6 to 7.1 mmag – in satisfactory agreement with the corresponding values for the reference R star. The formal uncertainties are rather conservative, as they include the errors from Poisson statistics, galaxy subtraction and magnitude calibration (see Ovvaldsen 2002 for details). We omit plotting error bars in the figures to increase clarity.

The most conspicuous features of the brightness data are the changes in A and B over a time span of the order of one year. It is found that A brightens by 0.12 mag in *R* and 0.15 mag in *V*, whereas B becomes fainter by 0.043 mag in *R* and 0.050 mag in *V*.

From Figs. 2 and 3 and Table 3, one might also deduce a small brightness decrease in A and B, in both colours, of 1–4 mmag/day. However, the individual data sets for each of the four consecutive nights reproduce little, if any, of this overall trend (see Sect. 5). For a discussion of the quasar variability over several weeks, see the recent paper by Ullán et al. (2003).

As the observing runs were separated by the approximate time delay of 416 days, we are now able to compare the brightness values of the A quasar component on 2000 January with the corresponding time-shifted ones of B (average of the 2001 March values). We find $V - R$ colour indices of 0.357 ± 0.007 mag for A and 0.318 ± 0.009 mag for B. Converting the $m_B - m_A$ differences from Table 3 into the physically significant B/A magnification ratios, we find values of 1.025 ± 0.011 in *R* and 1.062 ± 0.009 in *V*. These results are in qualitative agreement with Serra-Ricart et al. (1999), but not quite consistent with the achromaticity of the gravitational lens and the expected differential reddening of B due to its larger optical depth (see also Sect. 5).

4.4 Comparison with previous reductions

As regards the quasar variability in the two periods, our results – typically constant light curves in both colours during each night – do not support the many short time-scale fluctuations seen in fig. 1 of C03 (and C02). We therefore suspect that most of these fluctuations may be spurious and a likely reflection of problems arising from combining photometry from 12 different observatories. Likewise, failure to reject images of poor quality – whether due to image flaws or, more subtly, to inconsistent reference star photometry – will inevitably introduce systematic errors which may easily be misidentified as brightness fluctuations.

The A and B brightness levels for both observing runs, 2000 January and 2001 March, also differ significantly from those of C02 and C03. As an example, we find that during the observing nights in the *R*-band 2001 March, A and B were on average 16.397 and 16.492 mag, respectively, i.e. A brighter than B. C03 (fig. 1) finds ~ 16.37 (A) and ~ 16.30 (B), i.e. B brighter than A. The above authors perform a single correction, solely a function of seeing, to account for both galaxy light contamination and aperture crosstalk. If, however, we *omit* the galaxy subtraction and only apply our crosstalk correction, we get average values for A and B in perfect agreement with C03. (Note that our corrections not only account for seeing effects on each particular frame, but also for PSF ellipticity.)

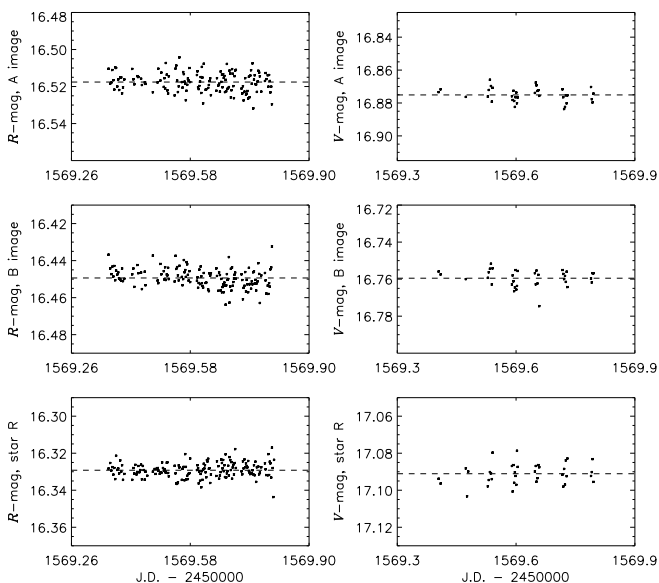


Figure 1. Results from photometry of QSO 0957+561A,B and star R in the *R*-band (left panels) and *V*-band (right panels) on 2000 January 25–26. There are 144/35 (*R*/*V*) unbinned data points for each quasar image. Dashed lines are the mean level.

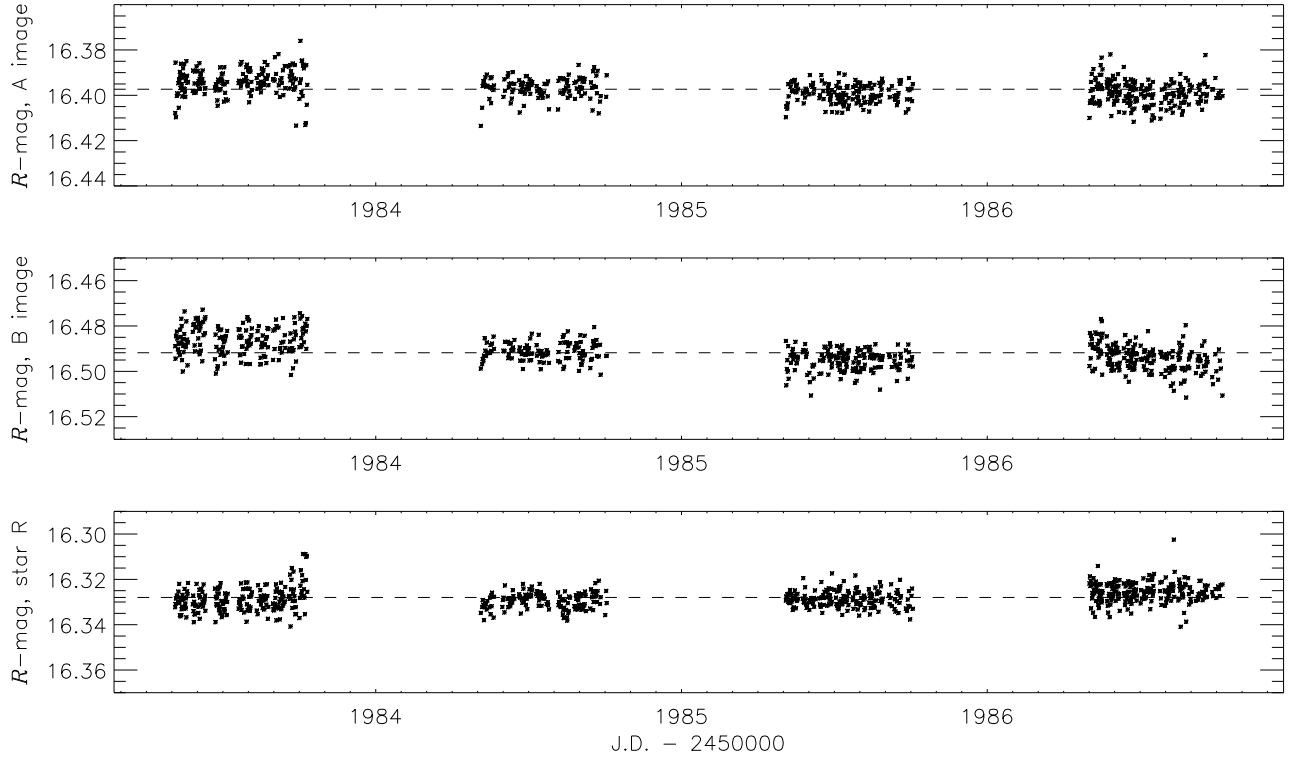


Figure 2. Results from photometry of QSO 0957+561A,B and star R in the *R*-band. Civil dates: 2001 March 14–18. There are 673 unbinned data points for each quasar image. The mean of all data points is plotted as a horizontal dashed line, and is only meant as a guide to the eye.

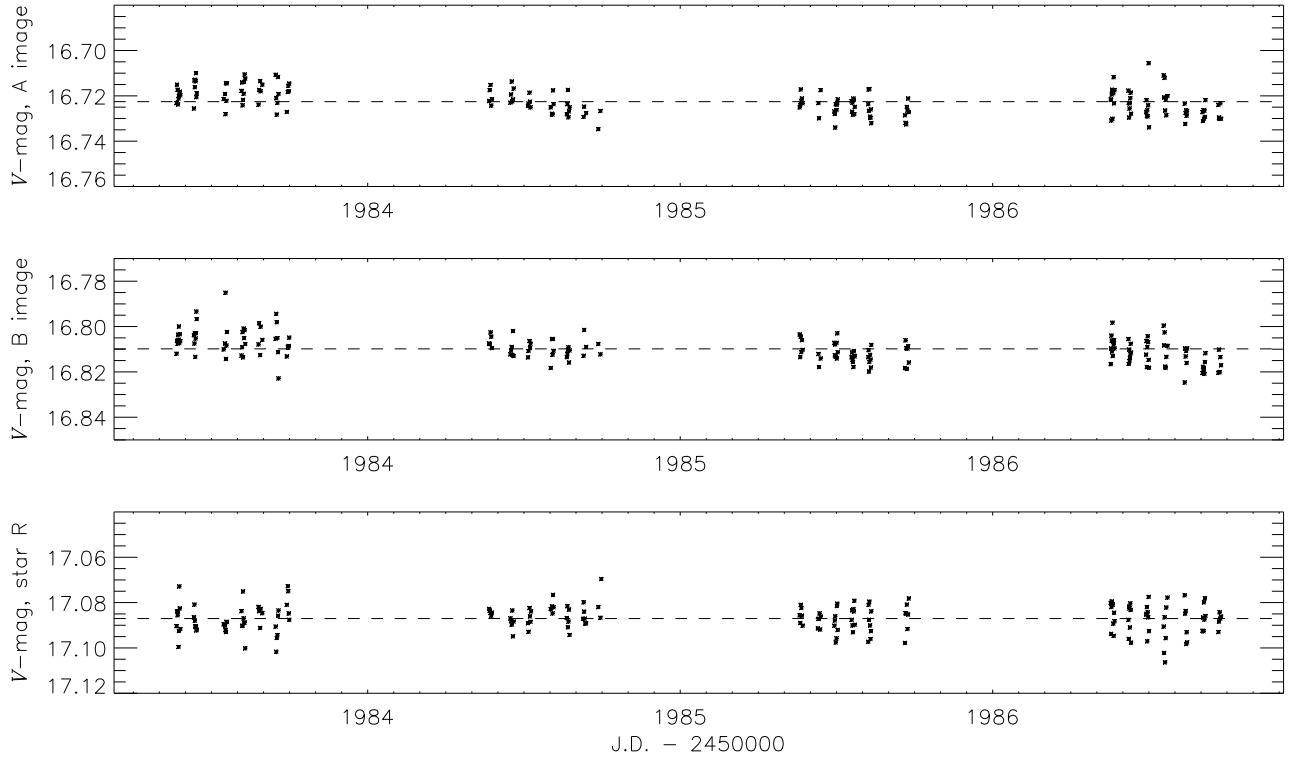


Figure 3. Same as Fig. 2, but in the *V*-band. Here there are 171 unbinned data points for each quasar image.

Table 3. Mean *R*- and *V*-magnitudes for the A and B quasar components and the R star for the 5 nights (see Figs. 1, 2 and 3). Numbers in parentheses are the standard deviations in mmag.

| Band | Object | 2000 Jan. 25–26 | 2001 March 14–15 | 2001 March 15–16 | 2001 March 16–17 | 2001 March 17–18 |
|----------|--------|-----------------|------------------|------------------|------------------|------------------|
| <i>R</i> | A | 16.518 (5.2) | 16.394 (5.7) | 16.397 (4.4) | 16.399 (4.0) | 16.399 (5.1) |
| | B | 16.449 (5.3) | 16.486 (6.2) | 16.491 (4.0) | 16.495 (4.4) | 16.494 (5.7) |
| | Star R | 16.329 (4.6) | 16.329 (5.4) | 16.329 (3.5) | 16.329 (3.5) | 16.326 (4.3) |
| <i>V</i> | A | 16.875 (4.3) | 16.718 (4.7) | 16.723 (4.7) | 16.725 (5.2) | 16.724 (5.4) |
| | B | 16.760 (4.5) | 16.806 (6.4) | 16.810 (3.9) | 16.812 (4.3) | 16.812 (5.8) |
| | Star R | 17.091 (5.6) | 17.088 (6.3) | 17.086 (4.8) | 17.087 (5.3) | 17.088 (6.8) |

5 DISCUSSION AND SUMMARY

A careful reduction with our new photometry scheme has yielded quasar light curves with little noise and hardly any outliers among the more than 2000 A and B data points. The photometry program seems to cope well with the large nightly variations in airmass, seeing, PSF ellipticity, sky level, and S/N-ratio, and produces remarkably constant light curves for each night. Our light curves do not exhibit any hourly fluctuations, in contrast to what e.g. Colley & Schild (2000), C02 and C03 have found. As a consequence, it seems impossible to derive any firm time delay from the observational material discussed here, let alone to obtain an estimate accurate to five significant digits, as the authors of C03 have been able to.

The small decrease from one night to the next for both quasar images, in addition to the typically constant behaviour during each night, might be regarded as a tentative, short time-scale manifestation of the much-debated ‘zero lag correlation’ (between the theoretically unrelated A and B light curves) present in the brightness record of QSO 0957+561 (Kundic et al. 1995; Colley et al. 2003; Ovaldsen et al. 2003). In the last reference, several conspicuous, simultaneous fluctuations were found in the quasar light curves, with time-scales of up to several months and amplitudes up to 0.2 mag. However, four nights of continuous monitoring do admittedly not suffice to draw any firm conclusions about this issue. It constitutes nevertheless a strong indication that the correlation is a hitherto unexplained *observational* effect.

If not due to intrinsic fluctuations or microlensing, the observed small brightness variations – and the possible zero lag correlation as well – might be ascribed to colour effects arising from, e.g., changing observing conditions in connection with the spectral mismatch between quasar and comparison stars. However, the same remarks as in Sect. 4.3 regarding the large nightly changes in observational parameters coupled with the constant nightly light curves render this explanation unlikely. It remains a puzzle, though, that the night-to-night trend is not reflected in the nightly observations. Likewise, Ullán et al. (2003) found unexplained day-to-day variations that were very similar in both A and B. Because we have both constant and densely sampled light curves during the course of each night, we can exclude at least seeing, ellipticity, airmass and sky level from the list of possible explanations.

Combining our 2000 January A data with the 2001 March B data, in both colour bands, we have been able to estimate the optical continuum magnification ratio of QSO

0957+561A,B as well as the colour indices of the quasar images. The results stated in Sect. 4.3 seem somewhat surprising. There is no obvious explanation of the fact that A is redder than B; see however Serra-Ricart et al. (1999) and Michalitsianos et al. (1997). Next, the values of the flux ratio B/A differ in *R* and *V* (1.025 and 1.062, respectively). This might be an effect of inadequate galaxy modelling in the *V*-band (Sect. 3.2), but it seems very *ad hoc* to us to re-adjust the galaxy photometry for this reason only. For comparison in the *R*-band, we note that in the period 1992 October – 1995 June (true dates corresponding to the unshifted A image), the magnification ratio B/A was fairly stable at ~ 1.05 , based upon the *R*-band data set treated by Ovaldsen et al. (2003). The most straightforward explanation for this change is that one or both quasar components are affected by (long-term) microlensing.

Assuming that the observed gradient of, say, 3 mmag/day is typical for the unsystematic brightness variations in QSO 0957+561, whatever their origin, it follows from a simple random-walk argument that its expected variability over a few weeks will be of the order of 0.02 mag, in good agreement with the investigation by Ullán et al. (2003). Over a decade, the variations will be of the order of 0.2 mag, and such amplitudes are easily found in the brightness record (e.g. Pelt et al. 1998; Ovaldsen et al. 2003).

In conclusion, we hope that future observations and careful photometric analysis of the data from the elusive QSO 0957+561 system will shed light on some of the unresolved questions discussed above, not to mention the issues of time delay, lens modelling, and source structure.

ACKNOWLEDGMENTS

The work reported herein is based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. We thank L. Goicoechea for exchanging ideas with us regarding variability and photometric problems relating to QSO 0957+561. The observations were made at the NOT by K. Kjærsmo, Ø. Saanum and A. K. D. Evans.

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